

# Masses and Radii of Low-Mass Stars: Theory versus Observations

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**Abstract.** Eclipsing binaries with M-type components are still rare objects. Strong observational biases have made that today only a few eclipsing binaries with component masses below  $0.6 M_{\odot}$  and well-determined fundamental properties are known. However, even in these small numbers the detailed comparison of the observed masses and radii with theoretical predictions has revealed large disagreements. Current models seem to predict radii of stars in the  $0.4\text{--}0.8 M_{\odot}$  range to be some 5–15% smaller than observed. Given the high accuracy of the empirical measurements (a few percent in both mass and radius), these differences are highly significant. I review all the observational evidence on the properties of M-type stars and discuss a possible scenario based on stellar activity to explain the observed discrepancies.

**Keywords:** binaries: eclipsing — binaries: spectroscopic — stars: fundamental parameters — stars: late-type

## 1. Introduction

Most of the stars in the Galaxy have masses well below that of the Sun. In spite of the numerous population, detailed investigations of the properties of low-mass stars has been often difficulted by their intrinsic faintness. However, the observation and study of low-mass stars is now a field in rapid development mostly because of the increasing number of deep photometric surveys and the advent of powerful instrumentation able to obtain spectroscopy of these faint stars. But also renewed interest arises from one of the “hot topics” of this past decade: exoplanets. Very low mass stars, brown dwarfs, and giant planets share many physical characteristics and their study and modeling is often intimately related.

Efforts in the theoretical description of low mass stars have been intense in recent years. Current stellar structure models of low mass stars have reached a high level sophistication and maturity (e.g., Chabrier & Baraffe 2000). However, theoretical progress has not been matched by observational developments because of the difficulty in obtaining accurate determinations of the physical properties of low-mass stars.



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The comparison of model predictions with observations is a central point. Only by limiting the number of free parameters can a stringent test of stellar models be carried out. Therefore, there is a strong need for stars with well-determined properties such as masses, radii, effective temperatures, metallicities and ages. Models will pass the test *only* if they are able to reproduce *all* of the observed stellar properties.

The best source of such high-quality stellar properties is the analysis of double-lined eclipsing binaries (EBs) in which the components are detached. Optimum results are achieved when the system components are similar (i.e., deep eclipses and two radial velocity sets). Unfortunately, the number of known EBs with M-type components is small because of the faintness of the stars and the often strong intrinsic variations due to magnetic activity. To complement the dataset, in recent years it has become possible to determine the radii of nearby M-type stars directly from IR interferometry. The current precision does not match that of eclipsing systems but the prospects are bright. Furthermore, planetary transit research has also contributed to our database of low-mass stars. Follow-up of OGLE transit candidates has uncovered a number of EBs with F-G primaries and M-type secondaries.

In this paper I review the current data on masses and radii of low-mass stars, including both EBs and stars with direct radius measurements, and compare them with the predictions of stellar models. As already pointed out by several authors (e.g., Torres & Ribas 2002), a highly significant discrepancy exists between observation and theory. Here I analyze possible reasons for such discrepancy.

## 2. Eclipsing M-type Systems

Eclipsing binaries with similar components yield the stellar physical properties potentially to an accuracy of 1–2%. Such data have often served as valuable benchmarks for the validation of structure and evolution models. For two decades only two bona-fide EBs with M-type components were known: The member of the Castor multiple system YY Gem (Torres & Ribas 2002), with components of spectral type M1 V, and CM Dra (Lacy 1977; Metcalfe et al. 1996), composed of two M4.5 Ve stars. These were the only two M-type EBs that had been well studied until Delfosse et al. (1999) reported the discovery of eclipses in the M3.5 star CU Cnc and Ribas (2003) carried out accurate determinations of the components’ physical properties. Very recently, three new M-type EBs have been studied in detail. These are BW3 V38 (Maceroni & Montalbán 2004), TrES-Her0-07621 (Creevey et al. 2005), and GU Boo (López-Morales & Ribas 2005). Unfortunately, the

Table I. Masses and radii of the components of double-lined EB systems with masses below  $0.8 M_{\odot}$ .

Name	Mass ( $M_{\odot}$ )	Radius ( $R_{\odot}$ )	Ref.
V818 Tau B	$0.7605 \pm 0.0062$	$0.768 \pm 0.010$	1
RXJ0239.1-1028 A	$0.736 \pm 0.009$	$0.735 \pm 0.018$	-
RXJ0239.1-1028 B	$0.695 \pm 0.006$	$0.710 \pm 0.016$	-
GU Boo A	$0.610 \pm 0.007$	$0.623 \pm 0.016$	2
GU Boo B	$0.599 \pm 0.006$	$0.620 \pm 0.020$	2
YY Gem AB	$0.5992 \pm 0.0047$	$0.6191 \pm 0.0057$	1
TrES-Her0-07621 A	$0.493 \pm 0.003$	$0.453 \pm 0.060$	3
TrES-Her0-07621 B	$0.489 \pm 0.003$	$0.452 \pm 0.050$	3
BW3 V38 A	$0.44 \pm 0.07$	$0.51 \pm 0.04$	4
BW3 V38 B	$0.41 \pm 0.09$	$0.44 \pm 0.06$	4
CU Cnc A	$0.4333 \pm 0.0017$	$0.4317 \pm 0.0052$	5
CU Cnc B	$0.3890 \pm 0.0014$	$0.3908 \pm 0.0094$	5
CM Dra A	$0.2307 \pm 0.0010$	$0.2516 \pm 0.0020$	6,7
CM Dra B	$0.2136 \pm 0.0010$	$0.2347 \pm 0.0019$	6,7

Ref.: 1.- Torres & Ribas (2002); 2.- López-Morales & Ribas (2005);  
3.- Creevey et al. (2005); 4.- Maceroni & Montalbán (2004);  
5.- Ribas (2003); 6.- Lacy (1977); 7.- Metcalfe et al. (1996).

quality of the available observations for BW3 V38 and TrES-Her0-07621 does not permit high-accuracy determinations of both masses and radii, which have uncertainties of up to 10–15%. GU Boo has well-determined physical properties that make it twin system of YY Gem. Table I gives the masses and radii of the components of these M-type binaries. Also listed in the table are the components of two eclipsing systems with masses below  $0.8 M_{\odot}$ : The Hyades EB V818 Tau (Torres & Ribas 2002) and RXJ0239.1-1028 (López-Morales et al., in prep.). These K-type stars can be useful to better understand the results of the comparison with stellar models.

Stringent tests of stellar models can only be carried out if the chemical compositions and ages of the EBs can be constrained. YY Gem and CU Cnc are interesting cases because their kinematic properties indicate that they belong to the so-called Castor moving group, with an age of approximately  $\sim 300$  Myr and solar metallicity. Using also kinematic criteria, it appears that GU Boo is an intermediate-age star in the galactic disk and probably its metallicity is not far from the solar value. CM Dra is most likely a Population II EB with sub-solar metallicity and an old age (of the order of 10 Gyr). The ages and metallicities of BW3 V38 and TrES-Her0-07621 have not been estimated. An important remark on the significance of stellar ages is that M-type stars have long evolutionary timescales once they have reached

the main sequence. Thus, the only relevant point to model comparisons is whether any of the studied EBs could be pre-main sequence (i.e., an age  $< 100$  Myr). Available evidence indicates that this is not the case.

### 3. Other M-type Stars with Masses and Radii

Besides double-lined EBs, other sources of masses and radii of low-mass stars have emerged in recent years. Spectacular developments in interferometry (such as the PTI or VLTI instruments) have made it possible to resolve nearby M-type stars and determine their angular diameters with uncertainties of just a few hundredths of a milliarcsecond. From those measurements and trigonometric distances, determinations of stellar radii can be carried out (Lane et al. 2001; Ségransan et al. 2003). The drawback of this technique is that the masses cannot be determined directly (unless the resolved M-type star belongs to a visual binary) but have to be inferred from calibrations. Fortunately, the empirical mass-luminosity relationship in the infrared K band is well defined and has little intrinsic scatter (Delfosse et al. 2000).

Follow-up of OGLE planetary transit candidates has uncovered a number of eclipsing systems consisting of main sequence F-G stars with M dwarf companions (Bouchy et al. 2005; Pont et al. 2005). Because of selection effects, their light curves have shallow and flat-bottom eclipses corresponding to the transit of the M-type star (the occultation not observable). Also, only the lines of the F-G components are visible in the spectra due to the large contrast. These restrictions imply that the masses and radii of the M-type stars have to be determined through some assumptions (some of which are model dependent). The resulting accuracies are in the range 5–20%. The masses and radii resulting from both interferometry and OGLE transit follow-up are listed in Table II.

### 4. Models versus Observations

An obvious test of the performance of low-mass stellar models is to compare the observational mass-luminosity diagram with theoretical predictions. Most of the checks of state-of-the-art models using the absolute magnitude in the V band have indicated good overall agreement but significant scatter in the measurements. Further works (e.g., Delfosse et al. 2000) have shown that such scatter is most likely caused by starspots since the same mass-luminosity relationship is much better defined in the infrared K band. From those tests, one may naively

Table II. Other low-mass stars with well-determined masses and radii.

Name	Mass ( $M_{\odot}$ )	Radius ( $R_{\odot}$ )	Ref.
OGLE-TR-114	$0.82 \pm 0.08$	$0.72 \pm 0.09$	1
GJ 105A	$0.790 \pm 0.039$	$0.708 \pm 0.050$	2,3
GJ 380	$0.670 \pm 0.033$	$0.605 \pm 0.020$	2,3
GJ 205	$0.631 \pm 0.031$	$0.702 \pm 0.063$	3
OGLE-TR-34	$0.509 \pm 0.038$	$0.435 \pm 0.033$	4
GJ 887	$0.503 \pm 0.025$	$0.491 \pm 0.014$	3
OGLE-TR-120	$0.47 \pm 0.04$	$0.42 \pm 0.02$	1
GJ 15A	$0.414 \pm 0.021$	$0.383 \pm 0.020$	2,3
GJ 411	$0.403 \pm 0.020$	$0.393 \pm 0.008$	2,3
OGLE-TR-18	$0.387 \pm 0.049$	$0.390 \pm 0.040$	4
OGLE-TR-6	$0.359 \pm 0.025$	$0.393 \pm 0.018$	4
GJ 191	$0.281 \pm 0.014$	$0.291 \pm 0.025$	3
OGLE-TR-7	$0.281 \pm 0.029$	$0.282 \pm 0.013$	4
OGLE-TR-5	$0.271 \pm 0.035$	$0.263 \pm 0.012$	4
OGLE-TR-78	$0.243 \pm 0.015$	$0.240 \pm 0.013$	1
OGLE-TR-125	$0.209 \pm 0.033$	$0.211 \pm 0.027$	1
GJ 699	$0.158 \pm 0.008$	$0.196 \pm 0.008$	2,3
GJ 551	$0.123 \pm 0.006$	$0.145 \pm 0.011$	3
OGLE-TR-106	$0.116 \pm 0.021$	$0.181 \pm 0.013$	1
OGLE-TR-122	$0.092 \pm 0.009$	$0.120 \pm 0.018$	1

Ref.: 1.- Pont et al. (2005); 2.- Lane et al. (2001);  
3.- Ségransan et al. (2003); 4.- Bouchy et al. (2005).

conclude that models are successful at predicting the properties of low-mass stars. However, this is a very restrictive comparison that uses only two of the several independent properties that define a star.

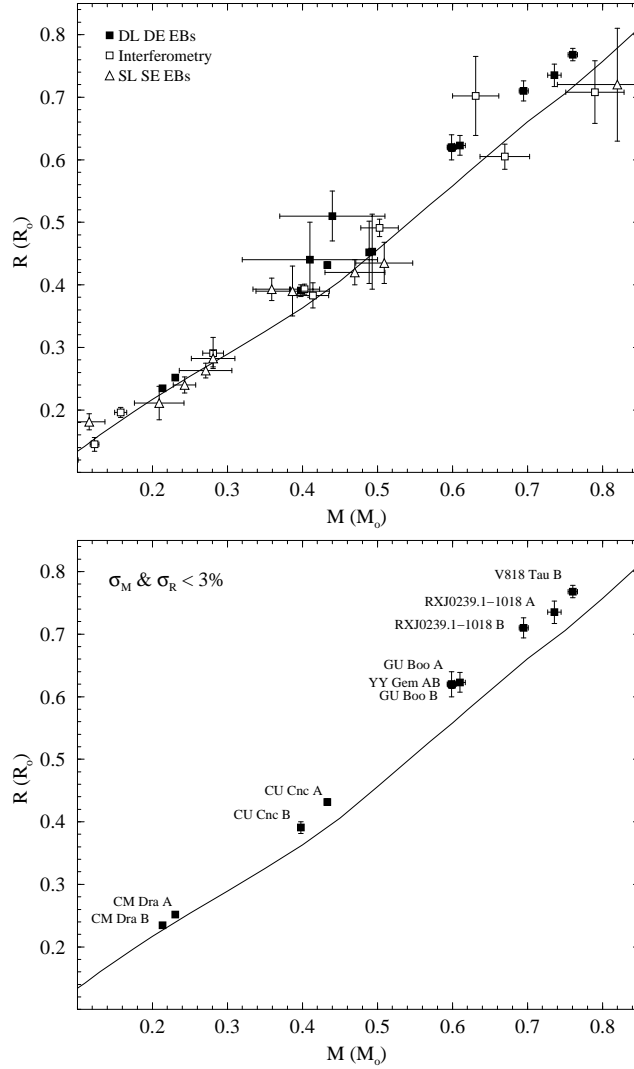
The accurate masses and radii of the stars described above offer an excellent opportunity to carry out critical tests to evaluate the performance of low-mass stellar models. Such tests have been carried out by a number of authors in the past (Popper 1997; Clausen et al. 1999; Torres & Ribas 2002; Ribas 2003), who have systematically pointed out a (rather serious) discrepancy between the stellar radii predicted by theory and the observations. Model calculations appear to underestimate stellar radii by  $\sim 10\%$ , which is a highly significant difference given the observational uncertainties. Furthermore, the comparisons in some case were made with virtually no free parameters since the ages and metal contents of the stars could be constrained independently.

With the extended stellar sample in this paper, the question of the comparison between theory and observation can be revisited. Empirical mass-radius diagrams are shown in Fig. 1 showing both the entire sam-

ple (top) and a subsample including those stars with masses and radii determined to better than 3% (bottom), which all happen to be EB members. The line represents a 300 Myr isochrone (i.e., main sequence) calculated with the models of Baraffe et al. (1998). Inspection of the top panel shows two mass intervals with different characteristics. Stars with masses below  $\sim 0.30\text{--}0.35\text{ M}_{\odot}$  seem to show small scatter and good agreement with stellar models, while the more massive have larger scatter and radii that tend to fall systematically above the theoretical line. These distinct mass regimes are not well established yet but it is tantalizing that the apparent division occurs near the limit between fully convective stars and stars with radiative cores.

The high-accuracy sample in the bottom panel of Fig. 1 leaves no doubt that a significant discrepancy exists between models and observations with regards to stellar radii. Other detailed comparisons have also shown that the stellar effective temperatures appear to be overestimated by  $\sim 5\%$ . This, together with the good agreement in the mass-luminosity plot, argues in favor of a scenario in which the stars have larger radius and cooler temperature than predicted by models but just in the right proportions to yield identical luminosities. A  $\sim 10\%$  radius underestimation is compensated by a  $\sim 5\%$  temperature overestimation to yield identical luminosities. What would explain such coincidence? The answer to this question is not clear yet, but there are some hints pointing in certain directions.

Perhaps the first question to address is whether the EB sample used to compare with models is representative of the low-mass star population. These systems are all detached and should have evolved like single stars. However, as members of close binaries (with periods less than 2.8 days) the components have undergone tidal interactions forcing them to spin up in orbital synchronism. The resulting high rotational velocities ( $10\text{--}60\text{ km s}^{-1}$ ) give rise to enhanced magnetic activity and thus to the appearance of surface spots, emission lines and X-ray fluxes. As shown in the work by Pizzolato et al. (2003), any M-type star with a rotation period below 10 days will experience these phenomena at their peak (saturated activity). It might be speculated that the larger radii and lower temperatures could be a reflex of such enhanced activity. Perhaps the significant spot areal coverage observed in these eclipsing systems has the effect of lowering the overall photospheric temperature, which the star compensates by increasing its radius to conserve the total radiative flux. Thus, there may be a correlation between the radius and the activity level of an M-type star. A similar conclusion of stellar activity causing the discrepancy between models and theory was reached in the recent study of Torres et al. (2005) for stars of higher masses ( $\sim 0.9\text{ M}_{\odot}$ ).



*Figure 1. **Top:** Mass-radius plot for stars in the lower main sequence with empirical determinations. The solid line represents a theoretical 300 Myr isochrone calculated with the Baraffe et al. (1998) models. **Bottom:** Same as above for those stars with determinations of masses and radii better than 3% (double-lined EBs).*

The sample we have used in our comparison may be representative of the population of active M-type stars only. This does not diminish the relevance of the discrepancy between models and observations. Low-mass stars with ages younger than a few Gyr are very active because they are generally fast rotators. Therefore, not only a star in a close binary system but any active M-type star (e.g., in a stellar cluster)

may have its radius severely underestimated if computed from stellar models. A definitive test of the magnetic activity hypothesis will have to wait for further observational data. In particular, EBs with periods  $\gtrsim 10$  days (i.e., not synchronized) and components of visual binaries resolved interferometrically should provide the necessary proof. Ongoing large scale surveys and future space missions, such as COROT or Kepler, are expected to increase the number of EBs significantly. If the activity correlation is firmly established, it will be time for theory to catch up by introducing magnetic activity in stellar evolution codes as a major ingredient influencing the observable properties of low-mass stars.

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